Jet Propulsion Laboratory
California Institute of Technology

Coronagraph Design and Operational Modes for the WFIRST CGI

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Exoplanet Detection

3,496 known exoplanets

exoplanets.nasa.gov

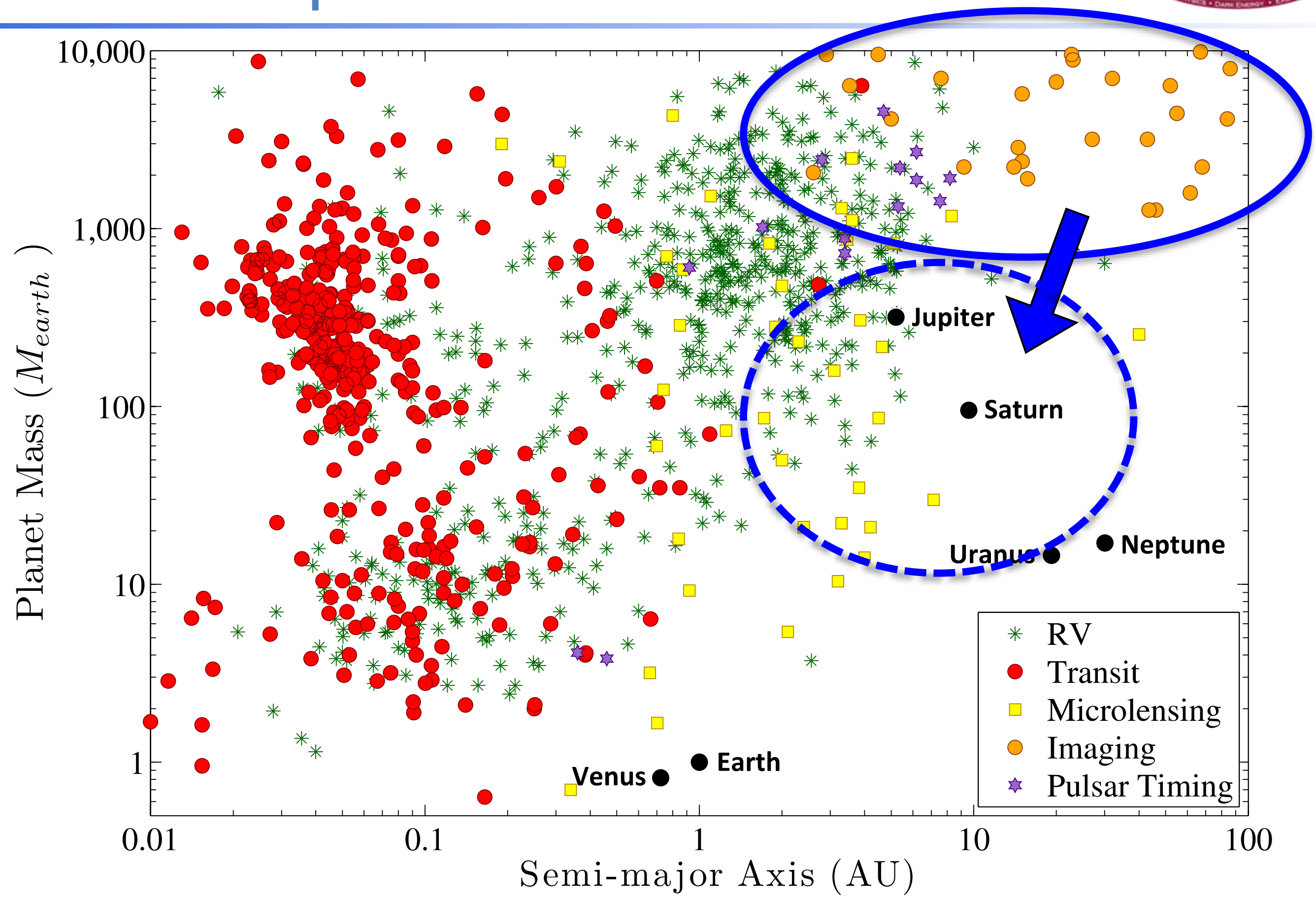
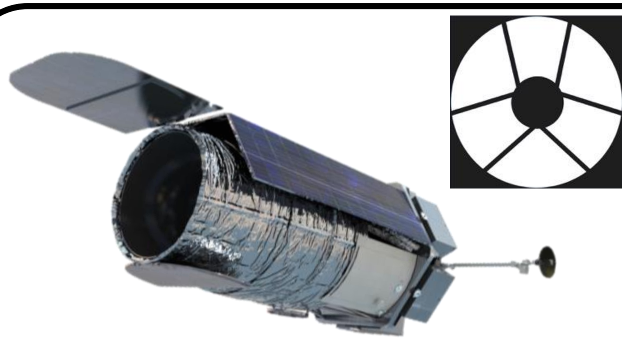


Image Data: exoplanets.eu

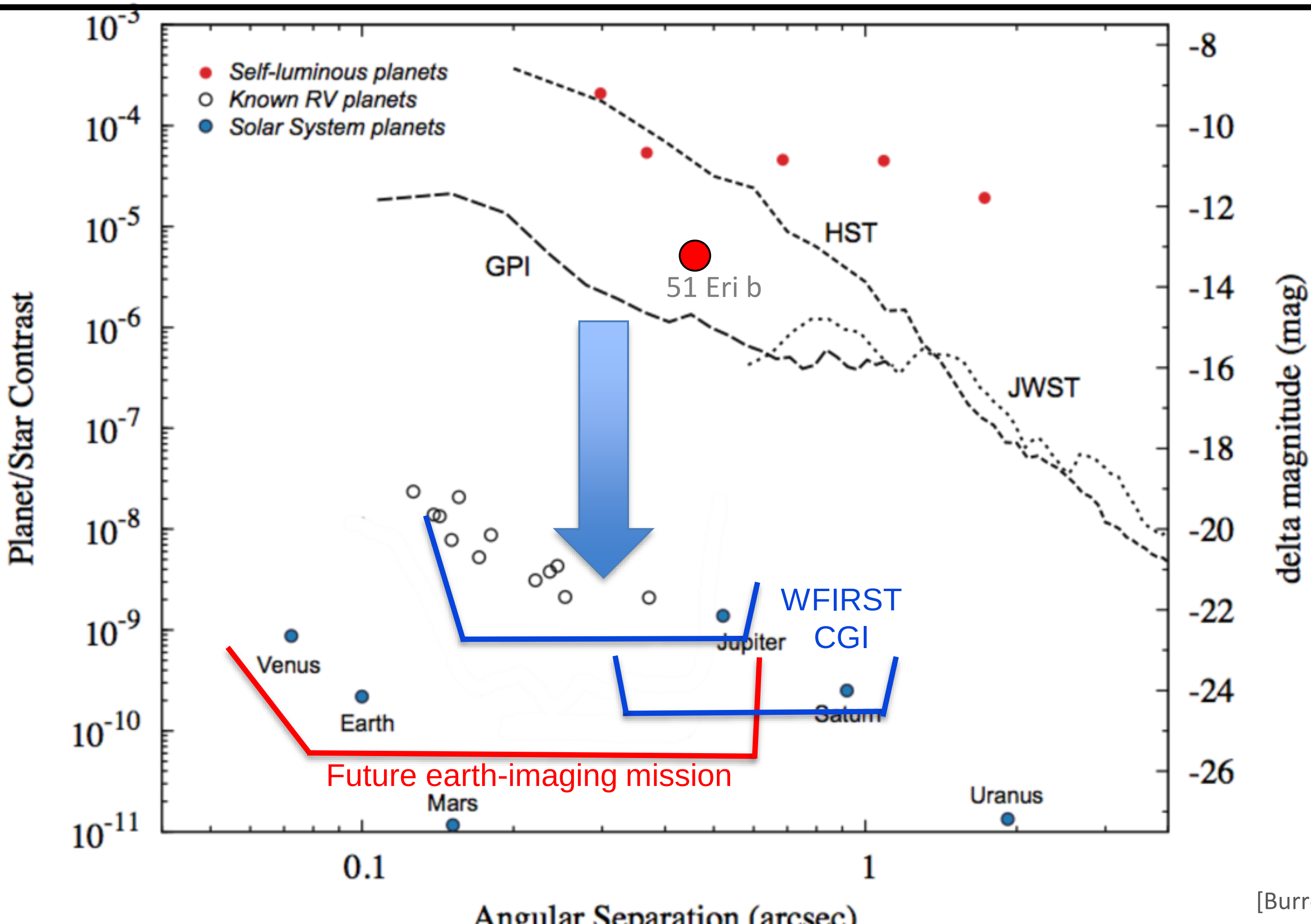
- Most planets discovered **indirectly**
- **Direct Imaging**: for spectra & more orbital parameters

Current and Future Observatories



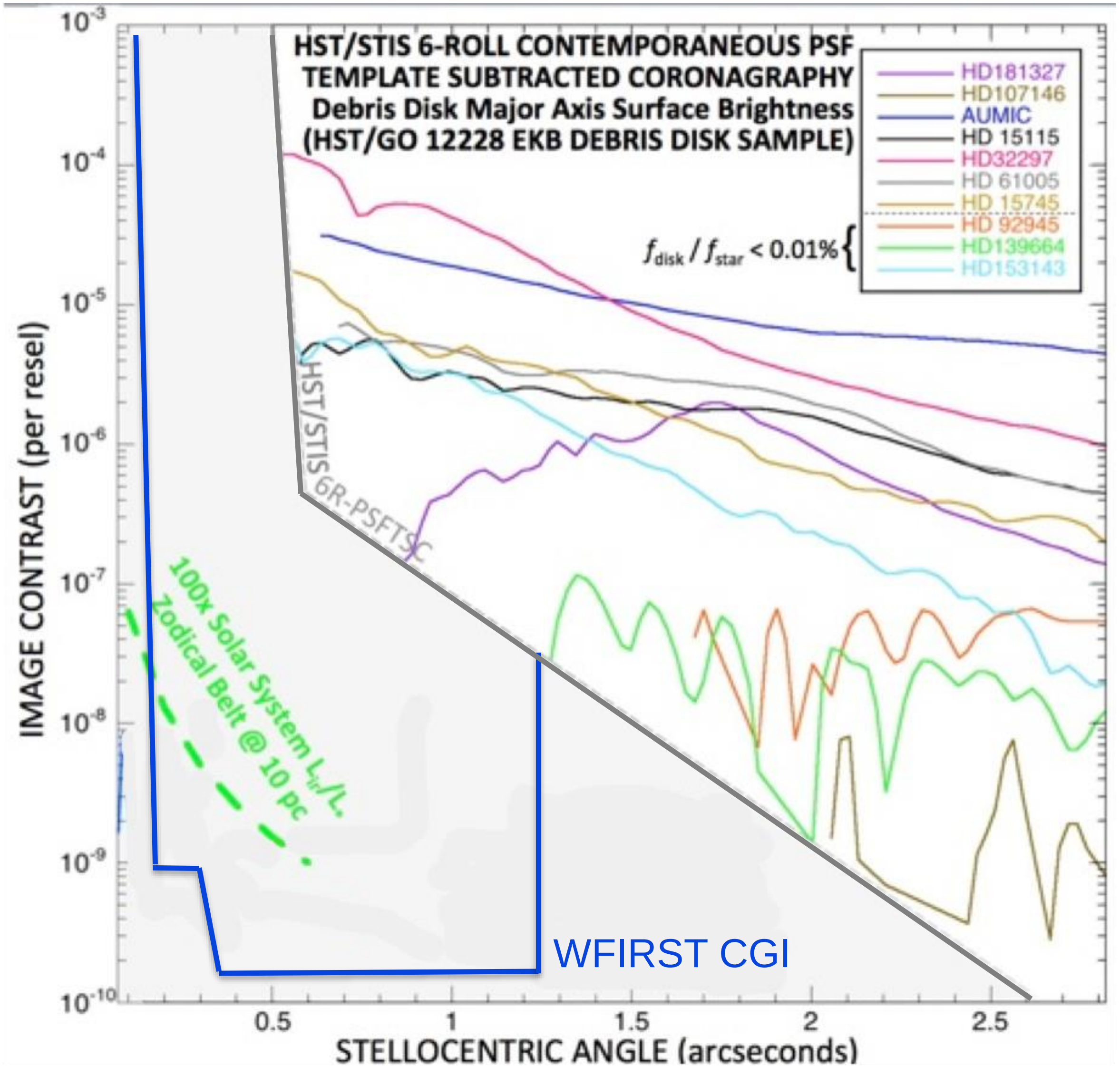
WFIRST Coronagraph Instrument (CGI)

- Launch in 2026
- <≈10^{-9} contrast at 150-1000 mas
- Visible-light imaging and spectroscopy for cold gas-giant exoplanets & inner debris disks



[Burrows 2014]

New Disk Science with WFIRST



[Scheider 2014]

Outline

1. Introduction

2. WFIRST CGI Modes and Design Choices
    a) Coronagraph design overview
    b) Explanation of CGI modes
    c) Adjusting for sensitivities

3. Coronagraph Design Research
    a) SPC-IFS
    b) SPC-Disk
    c) HLC

4. Summary

Coronagraph Design

Goals:
- **Maximize the science yield.**
- **Minimize risk.**

Design Parameters

Sensitivities to:
- **Pointing jitter**
- **Wavefront jitter** (coma, astig, focus)
- Primary mirror **polarization**
- Mask **misalignment**

Performance Metrics
- **Contrast**
- **Throughput**
- Spectral **Bandwidth**
- **Field of View** (IWA, OWA, angle)

Mask Properties
- Mask **shapes**
- Mask **materials**

Most of the design work in past 1-2 years has been to address sensitivities to aberration & misalignment.

Coronagraph Optimizer

Masks

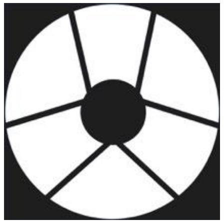
Instrument Simulator

Throughput, raw contrast

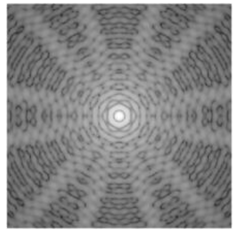
Science Yield Calculator

Types of WFIRST CGI Mode

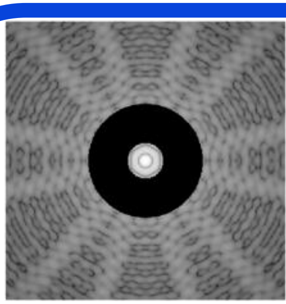
WFIRST pupil



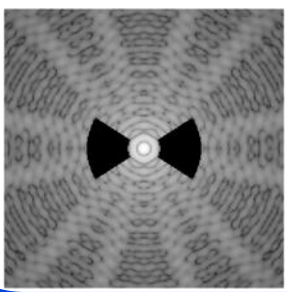
Nominal PSF



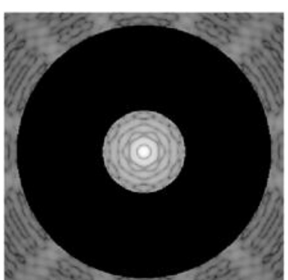
- **Three types of modes to achieve science goals:**



1. **<u>Hybrid Lyot Coronagraph (HLC):</u>** *exoplanet & inner disk imaging*
   - 10% BW, 360º FOV, 3-10 λ_0/D
   - ~4.0% core throughput



2. **<u>Shaped Pupil Coronagraph (SPC)</u>** for IFS: *exoplanet spectroscopy*
   - 18% BW, 2x65º FOV, 2.8-8.8 λ_0/D, lower sensitivities
   - ~3.5% core throughput



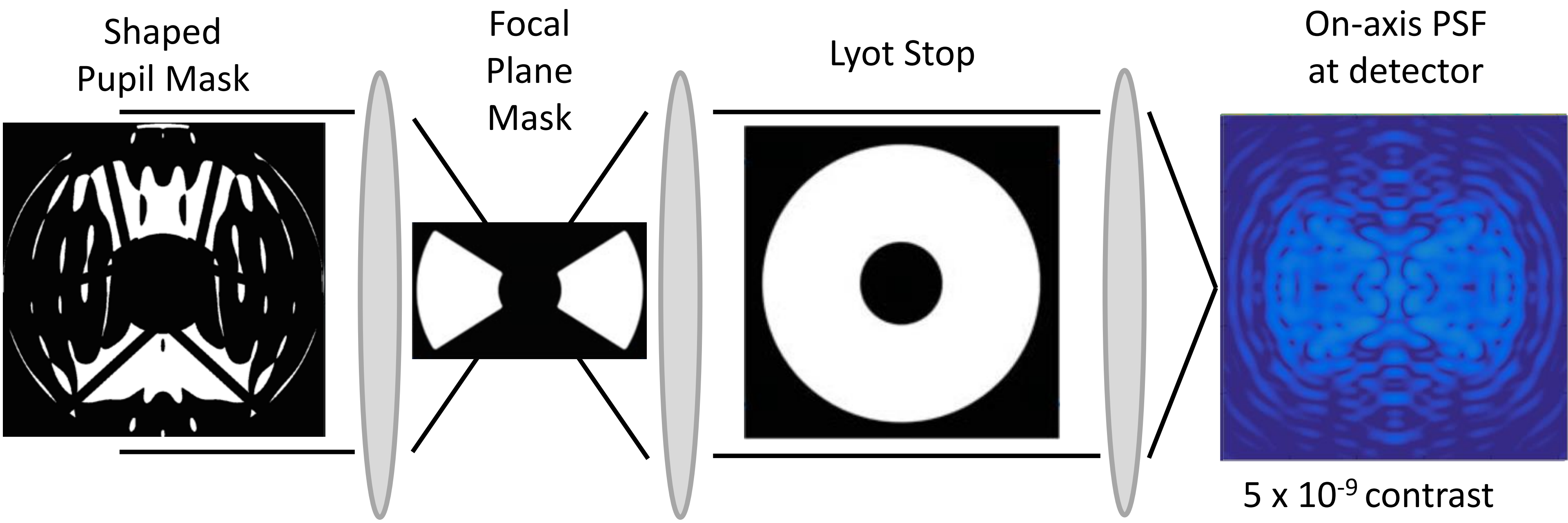
3. **<u>Shaped Pupil Coronagraph (SPC):</u>** *outer disk imaging*
   - 10% BW, 360º FOV, 7-19 λ_0/D
   - 5.5% core throughput

- Trauger et al. JATIS 2016
- Riggs SPIE 2014
- Zimmerman, Riggs, et al. JATIS 2016

How a Coronagraph Works

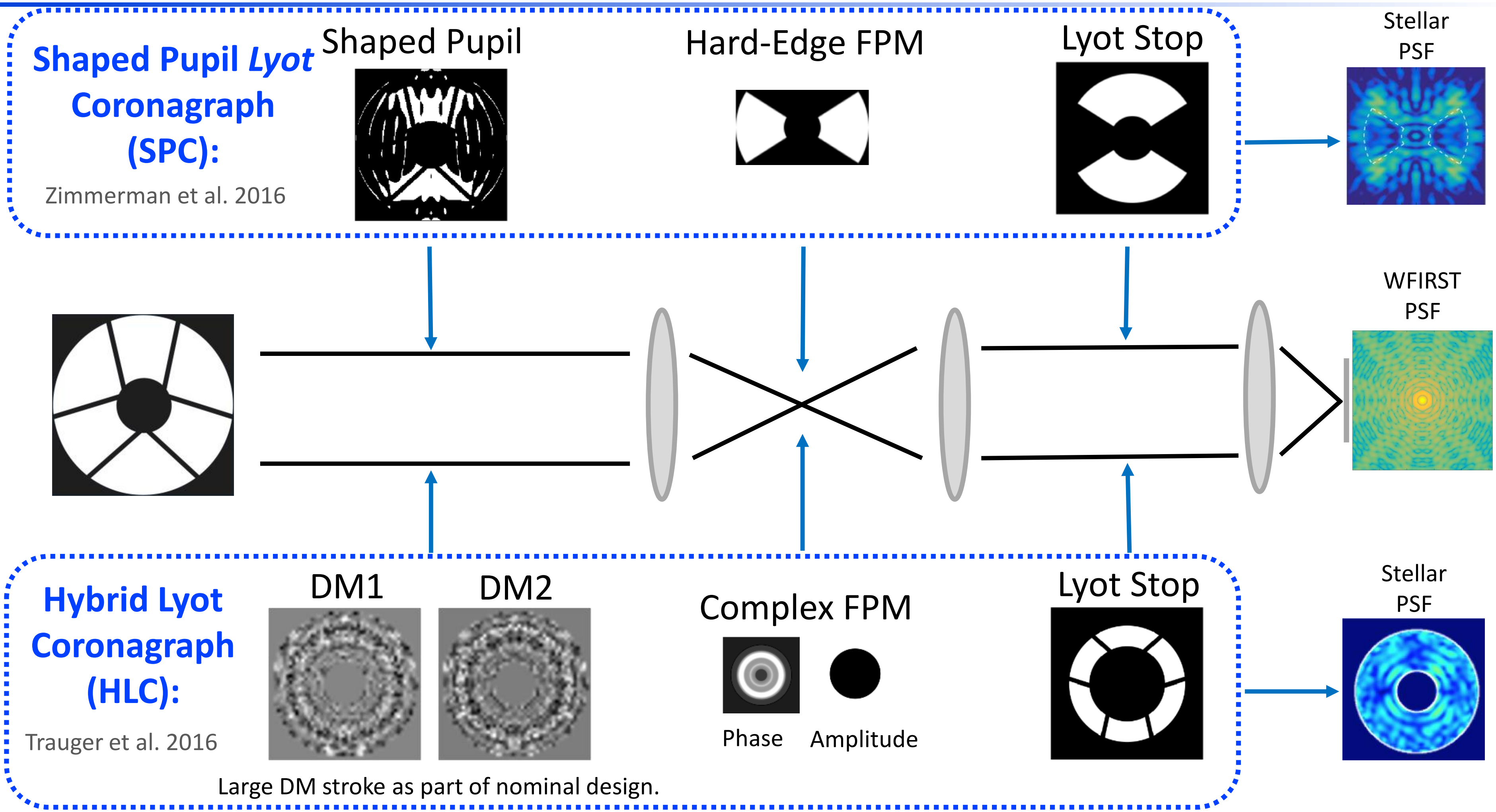
Shaped Pupil Lyot Coronagraph (SPLC)

Zimmerman, Riggs, et al. 2016



- For WFIRST, we use a combination of pupil-plane and focal-plane optics to suppress diffraction.

The WFIRST Coronagraphs



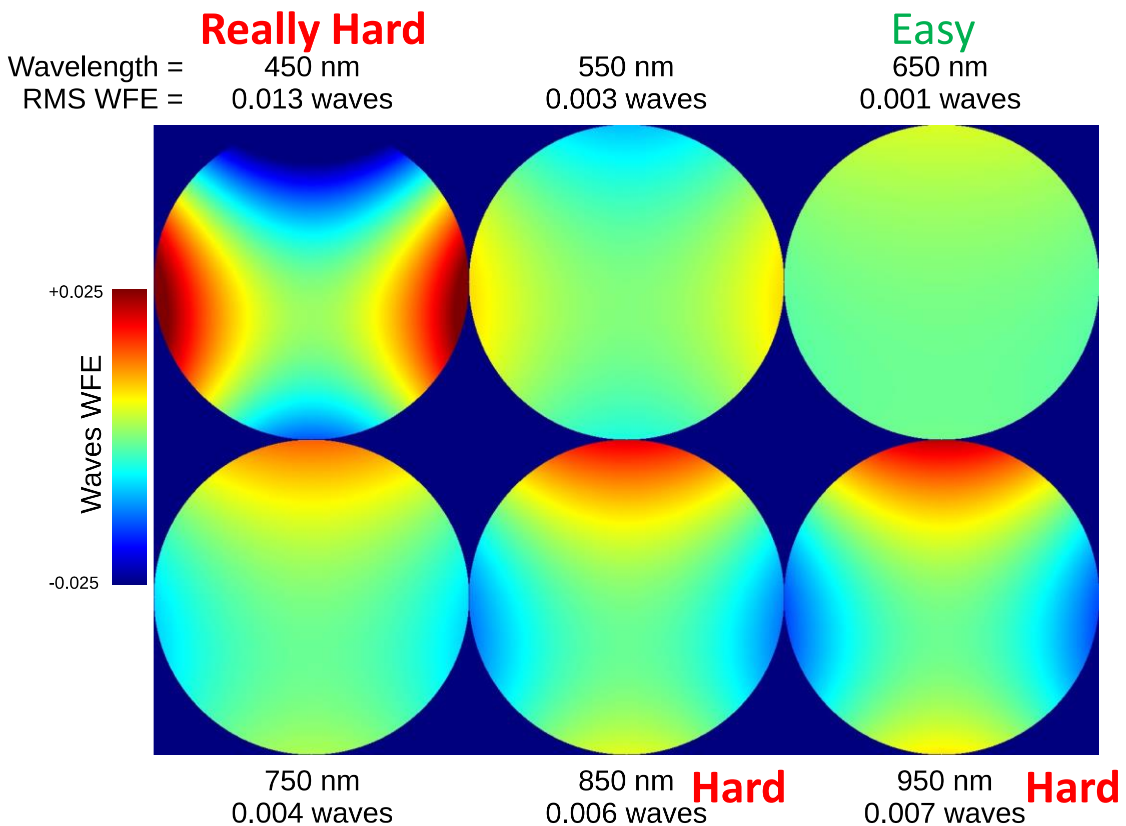
Benefits of Each Coronagraph:

- HLC: Full **FOV**, fewer masks, easier **alignment**
- SPC: Broader **bandwidth**, lower ab. **sensitivities** (esp. **PM pol.**), lower risk with DMs

Polarization-Induced Aberrations

> **The polarization from the primary mirror is a MAJOR design constraint.**

Cycle 6 Polarization: WFE_Y-WFE_X



This figure was already cleared in John Krist's presentation "Digging A Dark Hole: Models" *in April 2016.*

- <u>Differential polarization is mostly **astigmatism**</u>
  - Negligible near 600nm → **HLC**
  - Huge WFE far from 600nm → **SPC, or HLC+polarizer**
- Huge influence on our operational modes

HLC Sensitivities

***Note**: Band 1 moved to 508nm for less telescope polarization.*

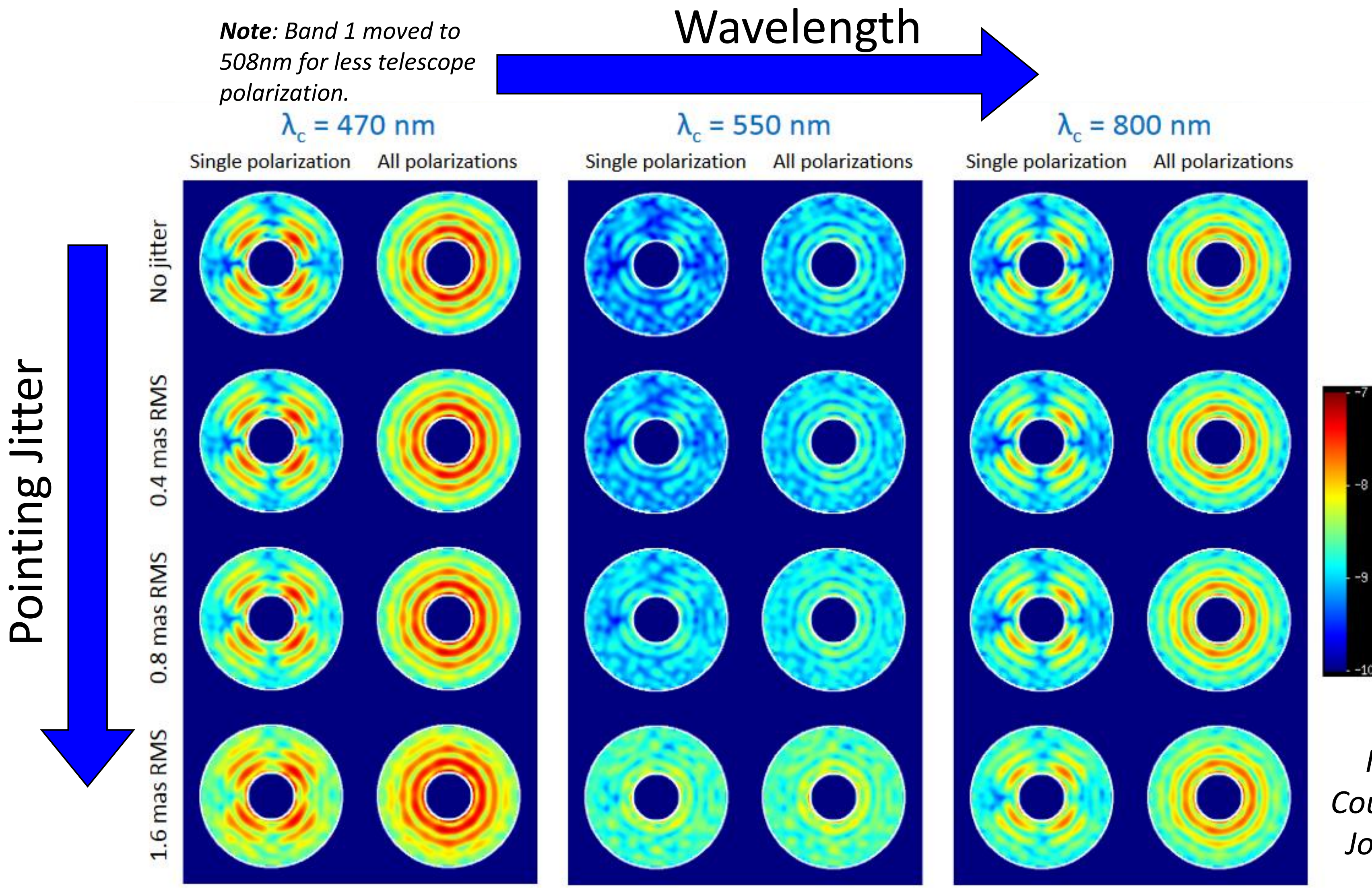
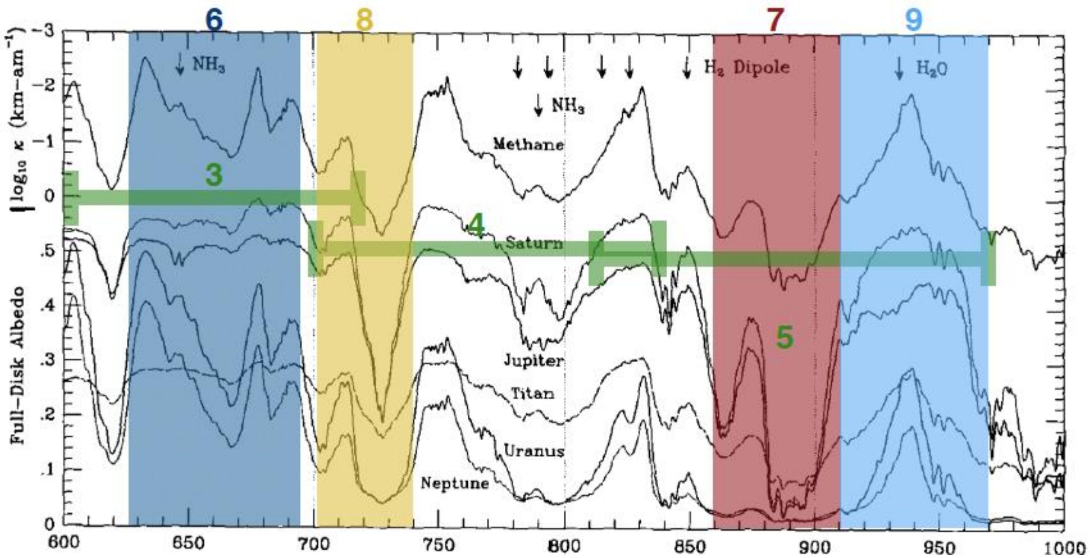


Image Courtesy of John Krist

This figure was already cleared in Feng Zhao's presentation "WFIRST Coronagraph Polarization Update – 11th Stanford Meeting" *in March 2017.*

- **Outside V-band, HLC better with analyzer.**
- Analyzer helps, but pol. cross-term still degrades contrast

CGI Science Bands



NOTE: No polarizers or field stops in IFS channel.

CGI Bands	λ_{center} (nm)	BW	Science Purpose	Imager or IFS	Coronagraph Type	Can Use Polarizer (for Science)	*Must* Use Polarizer (for Aberrations)
1	508	10%	continuum, Rayleigh	Imager	HLC	X	X (HLC)
2	575	10%	continuum, Rayleigh	Imager	HLC	X	
3	660	18%	CH4 spectrum	IFS	SPC		
4	770	18%	CH4 spectrum	IFS	SPC		
5	890	18%	CH4 spectrum	IFS	SPC		
6	661	10%	CH4, continuum	Imager	SPC	X	
7	883	5%	CH4, absorption	Imager	SPC	X	
8	721	5%	CH4 quantification	Imager	SPC (& HLC?)	X	X (HLC)
9	950	6%	water detection	Imager	SPC	X	

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SPC-IFS Design (2015-2016)

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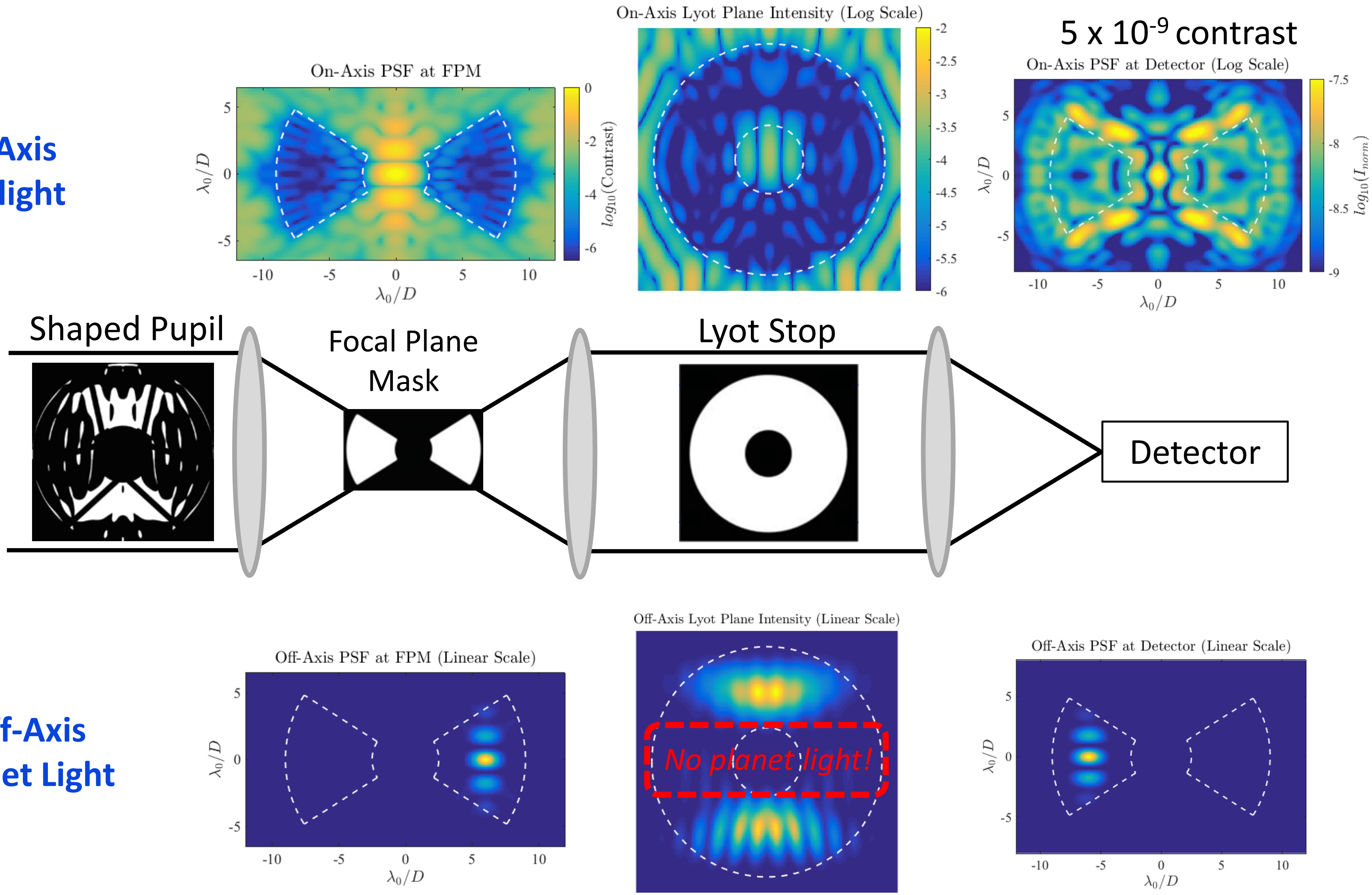
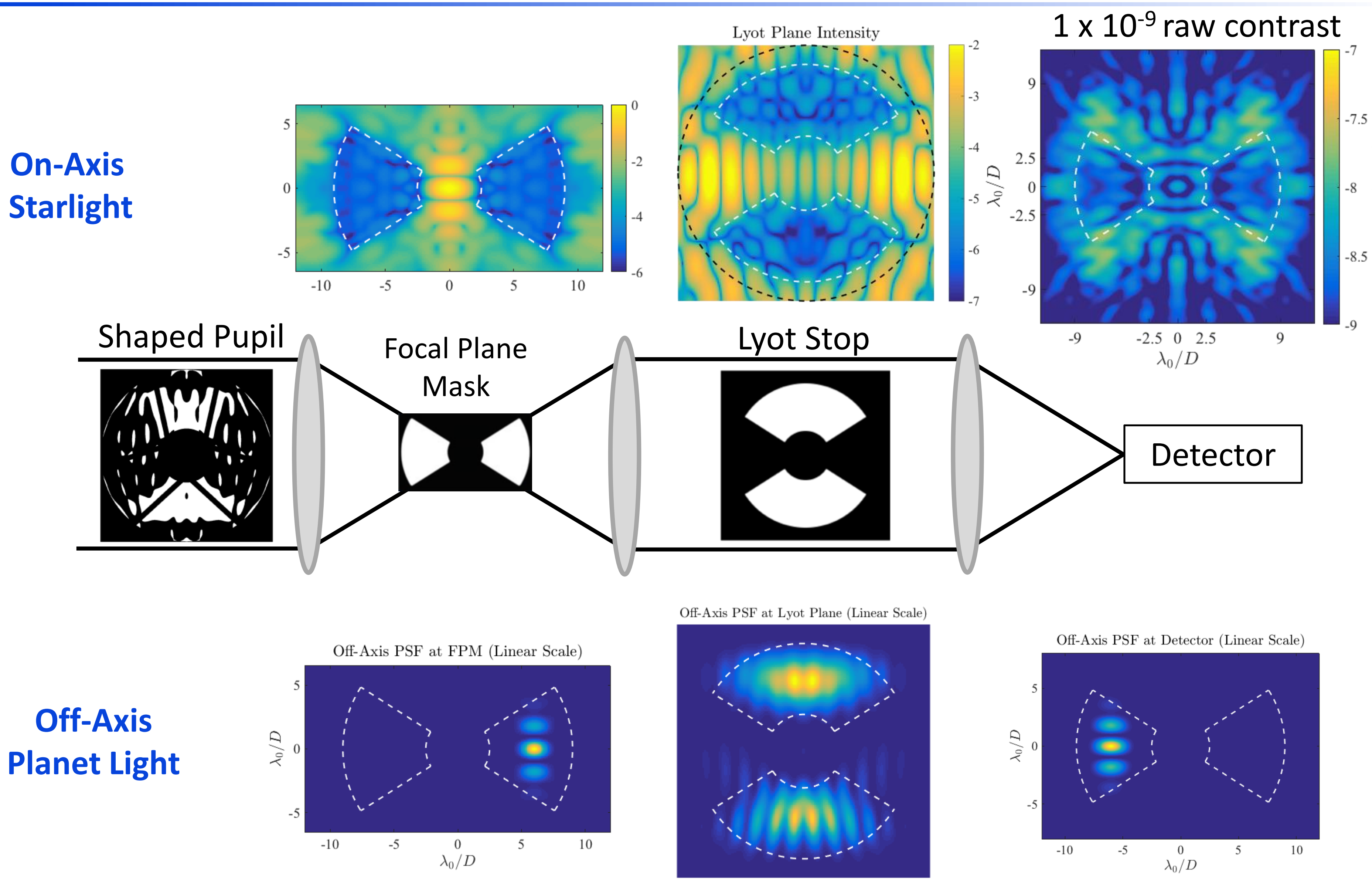
On-Axis Starlight

Off-Axis Planet Light



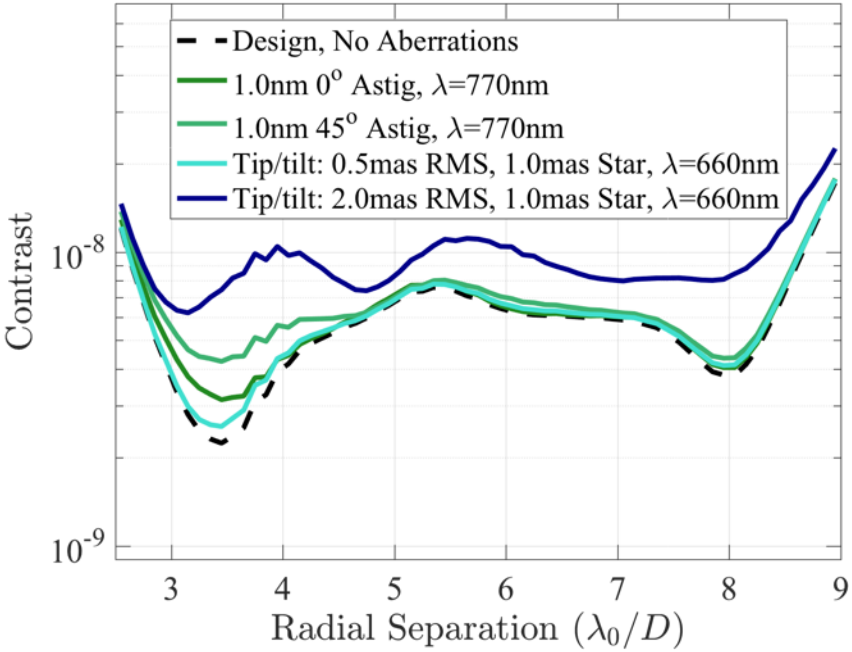
Zimmerman, Riggs, et al. 2016

SPC-IFS Design (June 2017)



SPC-IFS Performance Comparison

2015-2016 Design

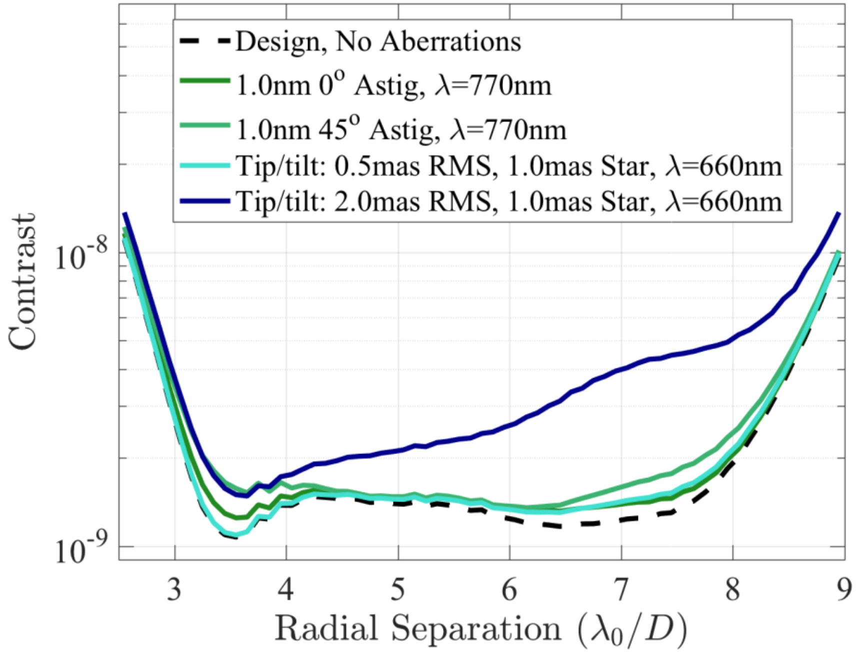


660 nm: <=3 spectra
770 nm: 0 spectra

(for design + 0.5 mas T/T jitter)

Example June 2017 Design

(not fully optimized yet)



- Much higher **contrast**
- Slightly higher **throughput**
- **Lower** T/T and astigmatism **sensitivities**

- Building design pipeline to maximize yield.

Planned Design Pipeline

1) SPLC-IFS Optimization Code

Python wrapper **Done**

Grid search over design variables. } **AMPL base code**

Masks from each design

2) Rapid Optical Simulator (MATLAB)

Simulate effects of: **Nearly Done**

1) Tip/tilt: jitter and stellar size

2) Differential **polarization** wavefronts.

3) [*Later*] **Empirical fudge factor**
   - From empirical (Monte Carlo) simulations of misalignments & aberrations.

Tables: Raw contrast, throughput, core area

3) Bijan's RV Planet Exposure Time Calculator (MATLAB)

Nearly Done

Vary input planet parameters.

Exposure times & # of Spectra

4) Human Review

- Look for highest yield designs.
- Learn why some planets are missed, and adjust design strategy to get them.

Optimization code modifications

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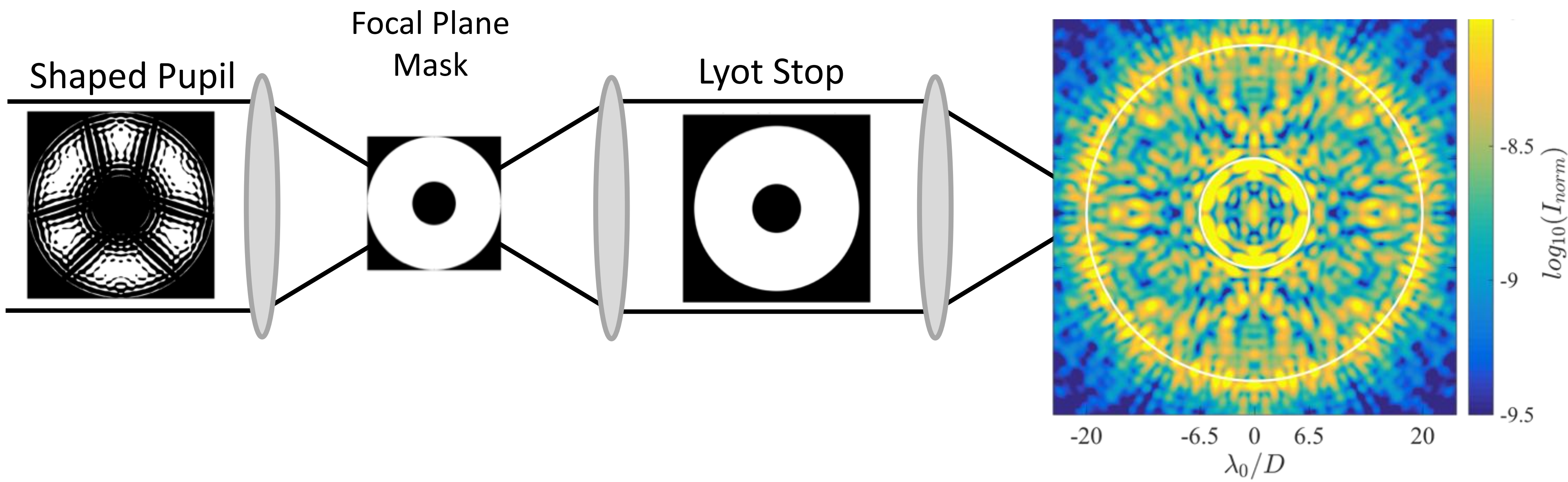
SPC-Disk Science Design

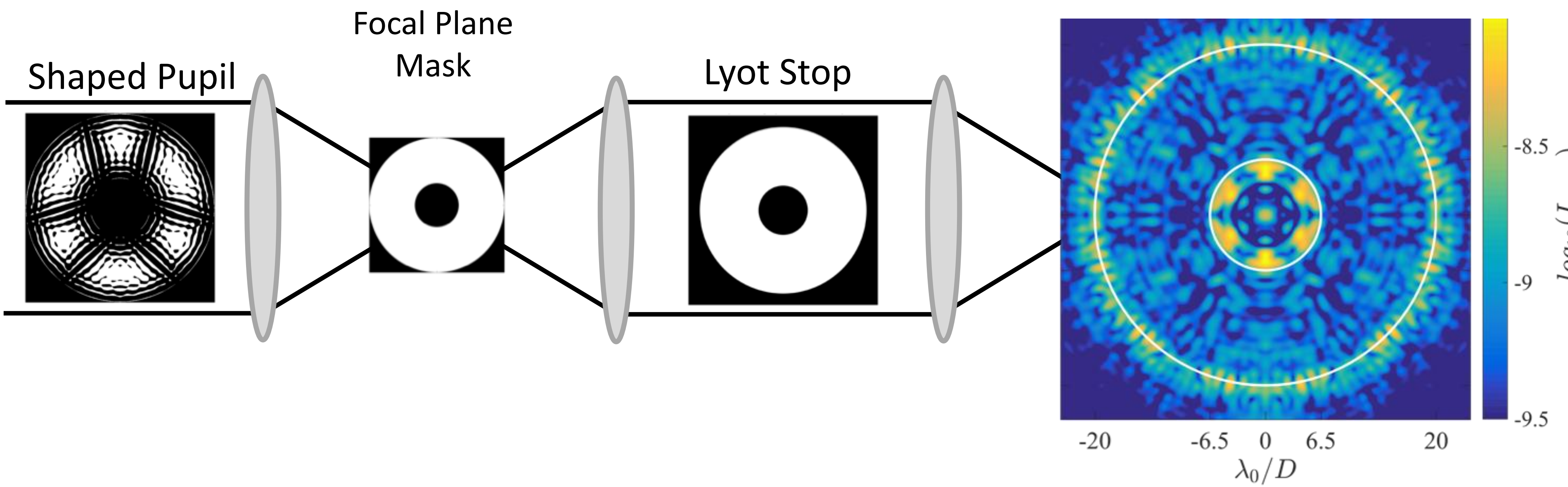
2015-2016 Design



Specs:
- **3.3 x 10^{-9}** contrast
- r=0.33-1.0” FOV (in V band)
- 10% Broadband
- Core throughput = 5.6%

SPC-Disk Science Design

2017 Design A

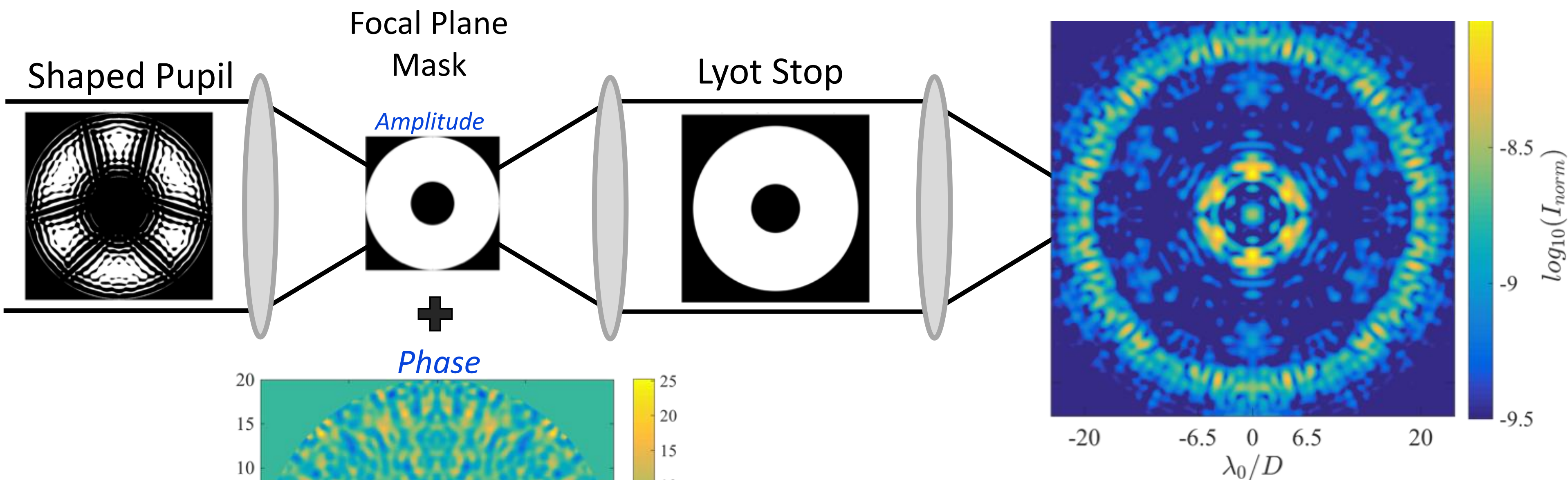


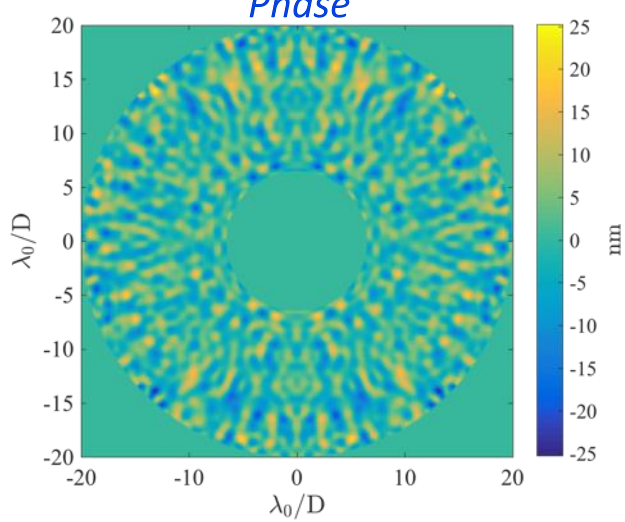
Specs:

- **6.5 x 10^{-10}** contrast ***(5x better)***
- r=0.33-1.0” FOV (in V band)
- 10% Broadband
- Core throughput = 5.5%

Hybrid SPC-Disk Design

2017 Design (Beta)





Specs:

- **3.4 x 10^{-10}** contrast ***(10x better)***
- r=0.33-1.0” FOV (in V band)
- 10% Broadband
- Core throughput = 5.5%

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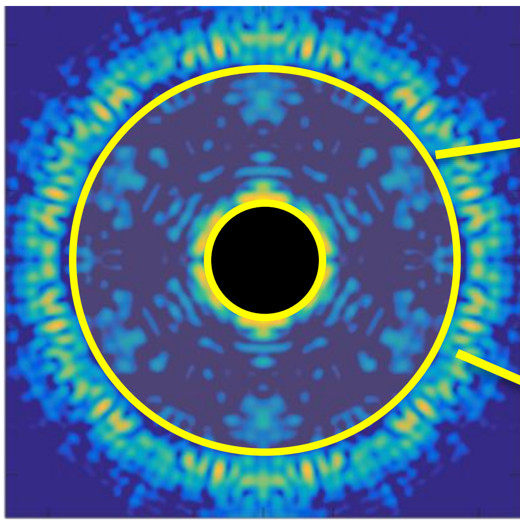
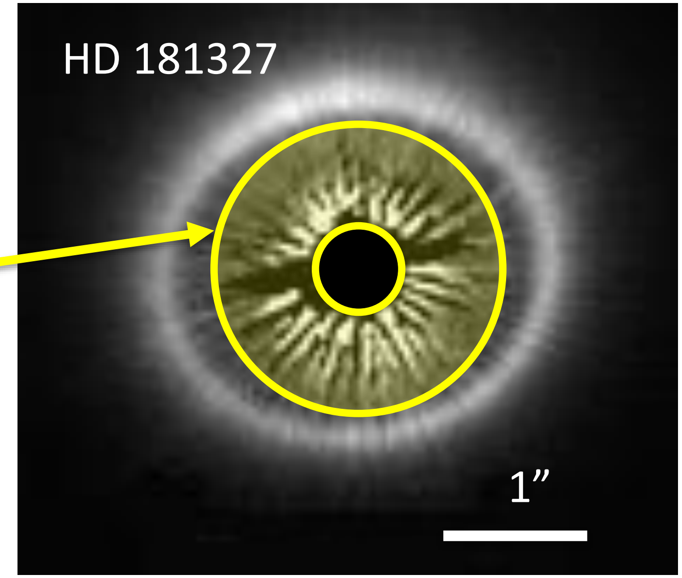
Disk Science

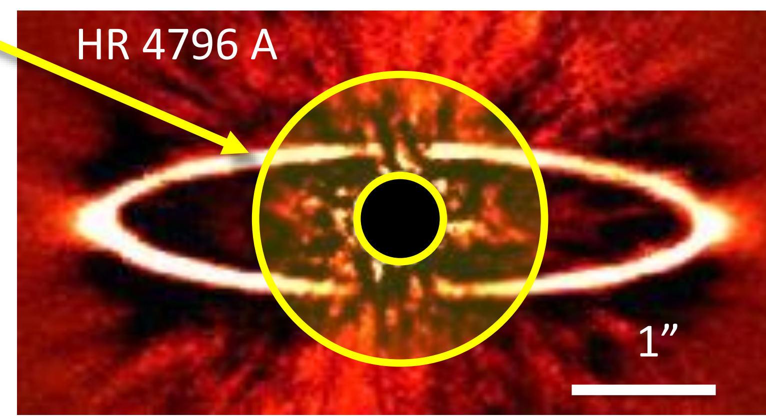
WFIRST CGI



HST STIS



VLT SPHERE



- 1.9” FOV in V band
- 10% Broadband
- 3.4 x 10^{-10} raw contrast

➢ ~2 minutes to get SNR=5 at 10^{-8} contrast for HD 181327

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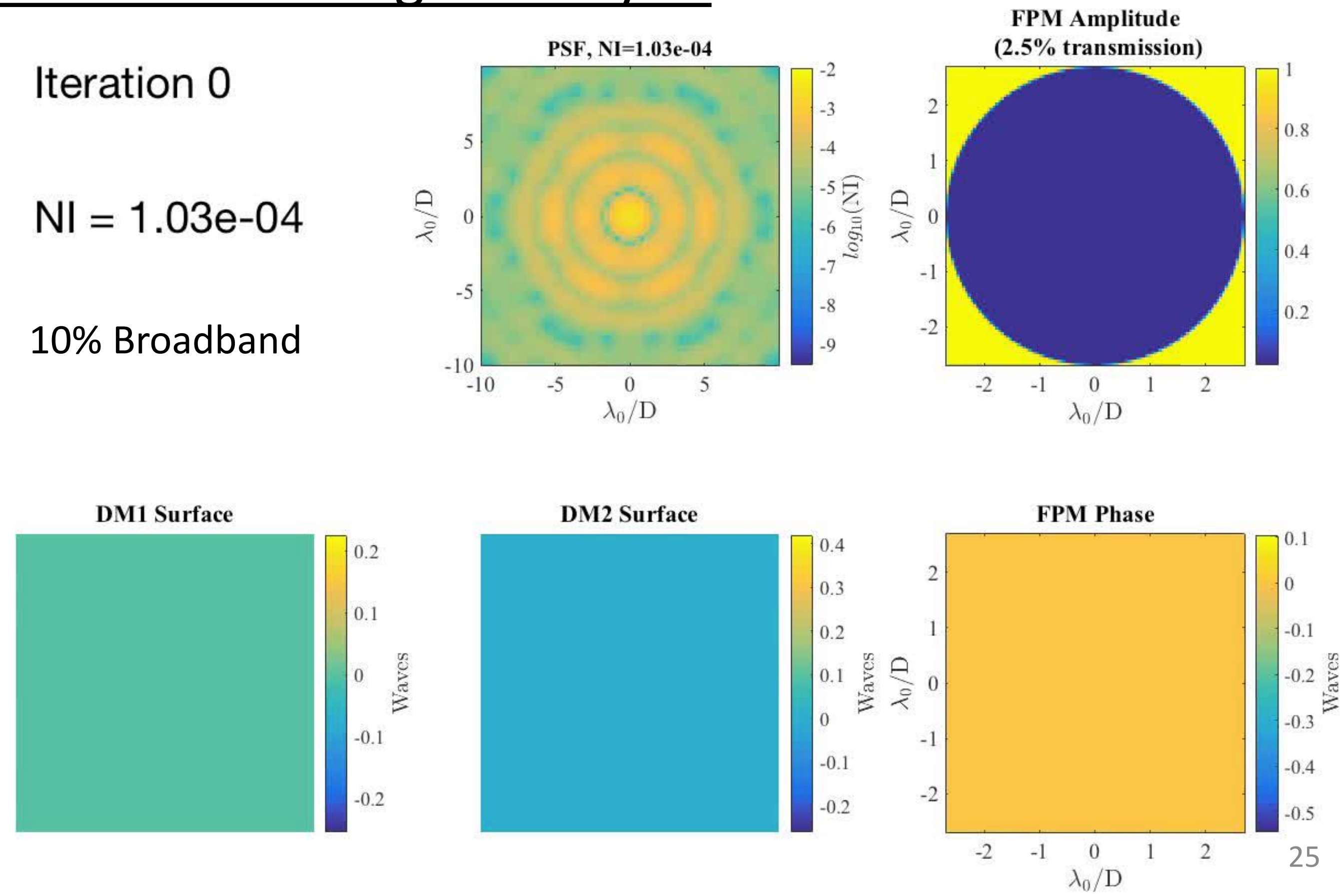
HLCs for Future Telescopes

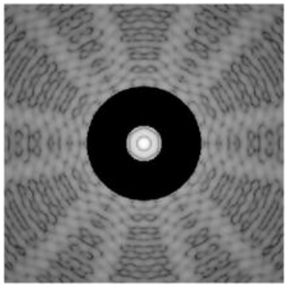
- The future of coronagraph design is **numerical optimization**.
  - Because of sensitivities and obstructed pupils.
- Hybrid Lyot Coronagraphs (**HLCs**) are
  - Manufacturable
  - High performance
  - Tunable
- <u>Need a **fast code** for HLC design surveys…</u>

FALCO:
FAst
Linearized
Coronagraph
Optimizer

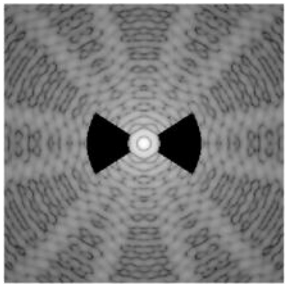


Summary of Modes

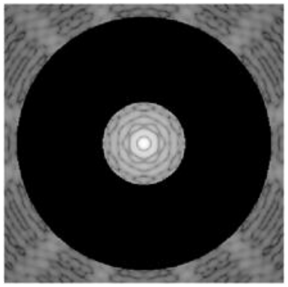
- To overcome **pupil obscurations** and **aberration sensitivities** and to **achieve science goals**, need **3 types of operating modes**:



1. **Hybrid Lyot Coronagraph (HLC)**: *exoplanet & disk imaging*
   - Full 360º FOV
   - Small IWA
   - Fewest masks (= lower complexity & cost)



2. **Shaped Pupil Coronagraph (SPC)** for IFS: *exoplanet spectroscopy*
   - 18% BW (for spectra)
   - Small IWA
   - Lower aberration sensitivities

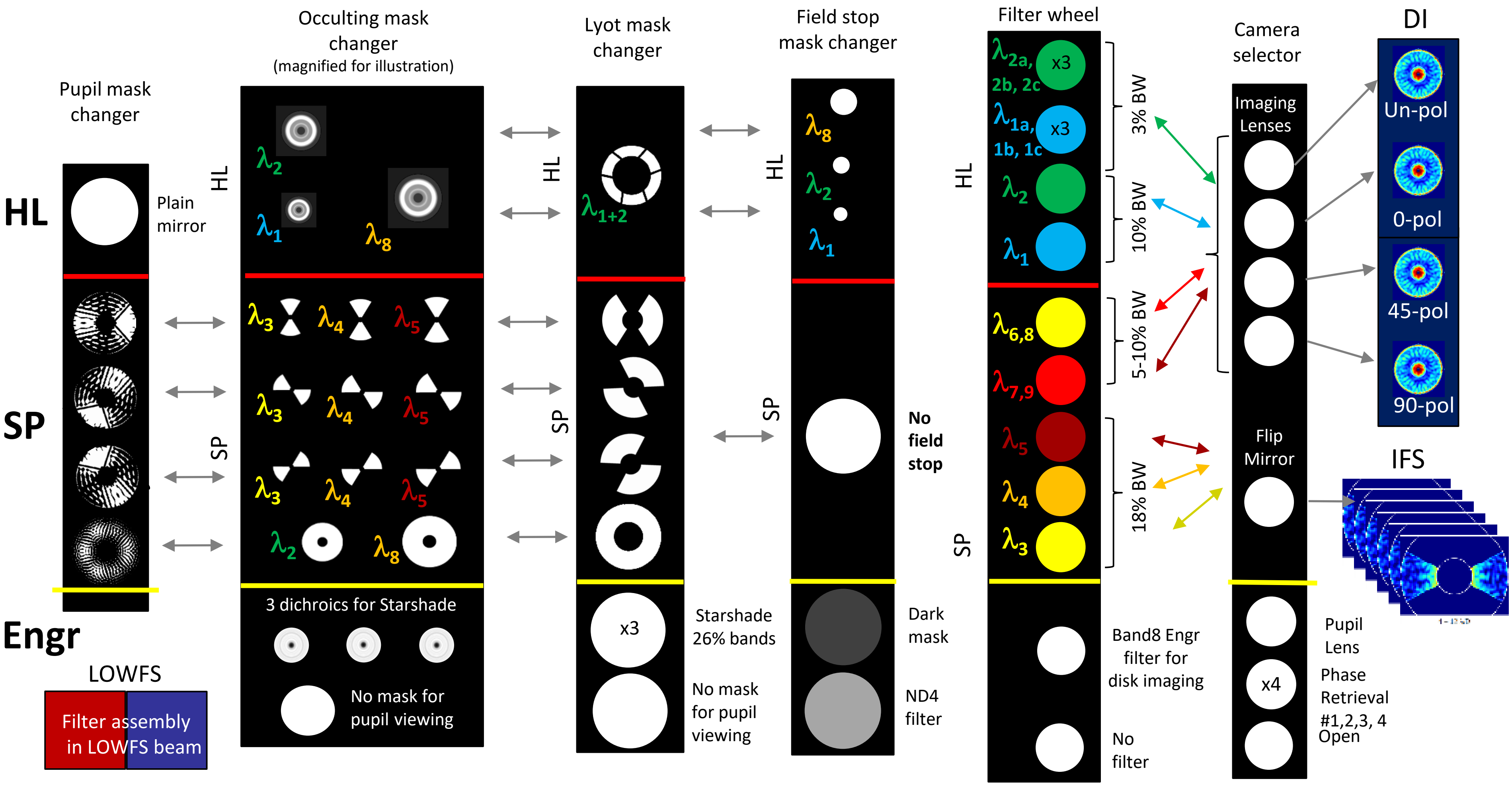


3. **Shaped Pupil Coronagraph (SPC)**: *disk imaging*
   - Full 360º FOV
   - Largest OWA

- Trauger et al. JATIS 2016
- Riggs SPIE 2014
- Zimmerman, Riggs, et al. JATIS 2016

Backup Slides

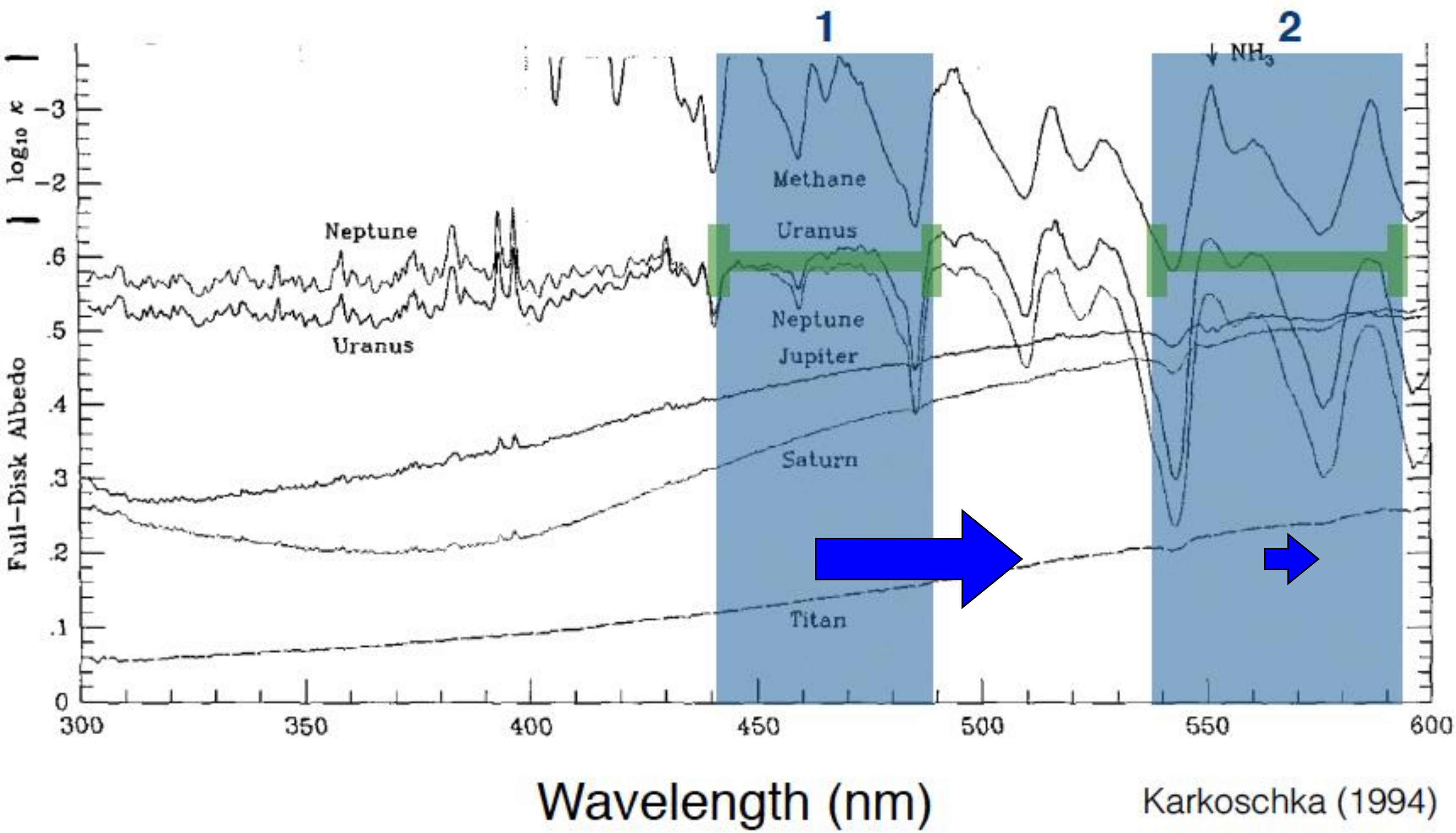
CGI Filter Wheel Populations



λ_1= 508nm λ_2=575nm λ_3=660nm λ_4=770nm λ_5=890nm

λ_{1a}= 491nm λ_{1c}= 524nm λ_{2a}=555nm λ_{2b}=594nm λ_6=661nm λ_8=721nm λ_7=883nm λ_9=950nm

CGI Science Bands 1 and 2



- Bands 1 & 2 shifted to longer wavelength because polarization WFE is too strong at B-band.